NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3834

EFFECT OF AMBIENT-TEMPERATURE VARIATION ON THE MATCHING REQUIREMENTS OF INLET-ENGINE COMBINATIONS AT SUPERSONIC SPEEDS

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SUMMARY

The effect of ambient temperature on the matching requirements of inlet-engine combinations has been analyzed for two typical turbojet engines up to a Mach number of 3.5. The changes in ambient temperature ordinarily encountered in flight can markedly influence the performance of matched inlet-engine combinations for engines operated at constant mechanical speed. Up to 30 percent of the capture mass flow may be spilled at the design Mach number because of typical variations in the ambient temperature. Thus, to avoid subcritical operation, the use of variable inlet features are required even at the design Mach number.

If features such as a bypass or a movable compression surface are to be used for efficient inlet-engine matching, the inlet should be sized for the lowest ambient temperature to be encountered. The capacity of such variable features must be appreciatively increased over that for a constant ambient temperature to prevent subcritical operation during off-design temperature operation. Moreover, the capacity of certain matching techniques may be inadequate if both variations in free-stream Mach number and ambient temperature are considered.

INTRODUCTION

When aircraft are operated over an altitude and climatic range, large variations in ambient temperature are encountered (ref. 1). In addition, a large variation in air temperature during a given season of the year is not unusual, even at the same altitude and geographical location. This variation may approach 80° F and can amount to a 25-percent change in absolute temperature. Although the effect of ambient temperature on turbojet-engine operation and performance is recognized, a "standard day" is usually assumed in order to simplify the procedure for matching the airflow characteristics of a supersonic inlet to those of a turbojet engine (e.g., ref. 2). If, as is present-day engine design practice, the engine operates at constant mechanical speed, any variation in compressor-inlet temperature causes a change in the corrected engine airflow rate, affects the engine performance, and upsets the match point of the engine and inlet.

It might be expected that all turbojet aircraft would suffer or benefit from ambient-temperature changes in a like manner and that no relative advantage exists for any particular aircraft. However, if positive inlet design measures are taken, the off-design-temperature inlet-engine matching can be improved. It is apparent that certain of these measures may be more effective than others.

Considerable effort is being expended on the problem of efficient inlet-engine matching at off-design Mach number conditions. Techniques developed for matching at off-design Mach numbers include variable inlet geometry and bypass air systems. Since the problem of matching as Mach number changes is similar to that due to ambient-temperature changes, consideration should be given to utilizing the same techniques for both matching problems. This report evaluates the magnitude of the effects of ambient-temperature changes on the matching requirements for two typical turbojet-engine airflow characteristics and examines the possibility of utilizing the usual inlet-engine matching techniques when, in addition, a change in ambient temperature is encountered.

SYMBOLS

A area, sq ft

A_c inlet cowl area, sq ft

M Mach number

$f(M_0)$ a constant, $(A^*/A_0) = M\left(\dfrac{1 + \frac{\gamma - 1}{2} M^2}{1 + \frac{\gamma - 1}{2}}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$

m_e/m_0 engine mass-flow ratio

m_s/m_0 spillage mass-flow ratio

P total pressure, lb/sq ft

P/P_0 inlet total-pressure recovery

t_0 ambient temperature, $^{\circ}R$

Δt_0 $(t_0 - 392)$, $^{\circ}R$

w airflow, lb/sec

γ ratio of specific heats

δ ratio of total pressure to NACA standard sea-level pressure of 2116 lb/sq ft

θ ratio of total temperature to NACA standard sea-level temperature of 519° R

Subscripts:

e engine

0 free stream

Superscript:

* conditions at Mach number of 1

RESULTS AND DISCUSSION

Ambient-temperature conditions are generally represented by one or more of the many "standard days." These typical temperature variations with altitude have been determined statistically from weather observations such as in reference 1. A frequently used reference day is the NACA standard day (fig. 1), which has the temperature decreasing linearly from sea level to 35,000 feet and then constant at 392° R from altitudes between approximately 35,000 to 100,000 feet. The two additional standard days shown on figure 1 reasonably represent the extremes which may be expected (ref. 1).

Changes in ambient temperature occur not only as altitude and geographical location change but also vary from day to day even during the same season of the year. The maximum and minimum summer temperatures observed at the same altitude (52,600 ft) at several localities are shown in figure 2. At San Antonio, Texas, for example, temperature variations up to 60° F would be encountered. Obviously, larger temperature changes will be encountered if, in addition, altitude, season, and location are varied.

The effect of inlet-air temperature on turbojet-engine performance is well known. If, for any part of its operation, the engine must be maintained at a constant mechanical speed, the corrected engine airflow will vary with changes in ambient temperature. Thus, even without a change in airspeed, varying airflow demands are made on the supersonic inlet supplying engine air. Without variable geometry the inlet operating condition can, therefore, deviate greatly from the design point.

The variation of the corrected engine speed parameter $1/\sqrt{\theta}$ with free-stream Mach number is presented in figure 3. This parameter represents the percent of corrected engine speed at rated mechanical speed and determines the corrected airflow the inlet must deliver. A family of ambient temperatures is shown in terms of the deviation in degrees Fahrenheit from the standard NACA temperature above 35,000 feet (392° R). It is quite apparent that if a turbojet engine is limited to a constant mechanical speed, corrected-engine-speed changes approaching 10 percent can often be encountered, even at a constant flight Mach number. With a constant-corrected-speed design this problem is eliminated and the inlet and engine airflows remain properly matched.

The severity of the change in corrected engine speed due to ambient-temperature variation on the inlet airflow required is a function of the particular engine airflow characteristics. Two different engine airflow curves (for hypothetical engines designated as A and B) have been assumed and since only the relative slope of the curve is important for the problem being considered, the curves are shown in nondimensional form in figure 4. These assumed curves are representative of current engine designs with most of the current engines falling close to the curve for engine B.

Figure 5 shows the effect of ambient temperature on the corrected engine airflow with the engines of figure 4 operated at constant mechanical speed. For temperatures below 392° R (negative Δt_0) the engine would require more corrected airflow than at an ambient temperature of 392° R since the corrected speed is increased. On the other hand, positive Δt_0 would result in a decrease in the airflow required. Because the airflow curve for engine B has a greater slope than that for engine A, engine B is more sensitive to changes in the ambient temperature. Nevertheless, with either engine an inlet must be capable of supplying a large range of corrected airflow at constant Mach number. Unless variable geometry is utilized to provide this required airflow range, serious deviation from the inlet design point will result.

It can be shown that

$$\frac{P/P_0}{m_e/m_0} = \frac{49.4\ A_c f(M_0)}{\left(\frac{w\sqrt{\theta}}{\delta}\right)_e} \tag{1}$$

Based upon this relation, the effect of ambient temperature on the inlet operating condition has been computed and is presented in figure 6. For convenience the subcritical diffuser efficiency was assumed equal to the critical and design value. If the inlet does not include features designed to compensate for ambient-temperature variations, temperatures below design will result in supercritical operation (fig. 6(a)), while temperatures above design will result in subcritical operation (fig. 6(b)).

Since at 60,000 feet the ambient temperature may be as much as 58° F (see fig. 1) less than the reference value (392° R), the inlet may be forced to operate supercritically and, for engine B, with as much as a 20-percent reduction in pressure recovery. At the same time the velocity distortion at the compressor face would be increased considerably over the value at critical inlet operation. On the other hand, at this altitude the ambient temperature may reach 33° F higher than the reference value. If a constant subcritical inlet pressure recovery were assumed, mass-flow spillage reaching 8 to 12 percent of the supercritical mass flow would result. If, as is usually the case, the pressure recovery decreased subcritically, the spillage would be even greater, increasing the same percentage as the decrease in recovery (see eq. (1)). This spillage causes a large increase in the external drag and may put a fixed-geometry inlet into buzz. Because of these serious departures from design-point inlet operation, it would appear that, in addition to variable geometry for Mach number matching, inlets must be provided with features designed to compensate for ambient-temperature changes at a given free-stream Mach number.

In order to illustrate the effect of ambient-temperature variations on inlet design, the capture area and spillage requirements have been computed for the two assumed engines up to a free-stream Mach number of 3.5. A constant inlet kinetic energy efficiency of 0.92 at design was assumed. Three values of ambient temperature were considered, 334°, 392°, and 425° R. These conditions correspond to the range in temperatures encountered at an altitude of 60,000 feet (fig. 1).

The inlet capture area required for critical inlet operation is presented in figure 7. The lowest ambient temperature requires the largest inlet. For example, at a Mach number of 3.5 the inlet for engine A would have to be 20 percent larger on an Air Force cold day than on an Air Force hot day. For engine B the inlet would have to be 44 percent larger. It is interesting to note that engine B, which has the smaller change in capture area with flight Mach number, has the larger change with ambient temperature. Both of these effects are due to the steeper slope of the engine airflow curve.

If the inlet does not have a variable capture area, it is usually sized for the flight condition requiring maximum area. At off-design conditions the excess inlet flow m_s/m_0 is spilled subcritically or by means of a translating compression surface or a bypass.

With the inlet sized at a free-stream Mach number of 3.5 for the NACA standard day above 35,000 feet (ambient temperature, 392° R), the spillage at the three temperatures would be as shown in figures 8(a) and (b). For ambient temperatures above 392° R the off-design spillage is increased. For temperatures below 392° R, the off-design spillage is reduced, and unless additional airflow were supplied, the inlet would be forced to operate supercritically over at least a part of the speed spectrum. Since supercritical operation is generally undesirable because of reduced pressure recovery and increased velocity distortions at the compressor face, it is concluded that the inlet should be sized for the cold day (figs. 8(c) and (d)). When so sized, the hot-day spillage is increased. However, calculations indicated that the thrust penalty due to the increase in estimated bypass spillage drag is less than that associated with cold-day supercritical operation of a standard-day inlet design.

Thus, when ambient-temperature variations are considered in the design of an inlet employing variable geometry for inlet-engine matching, the inlet should be sized for the lowest temperature to be regularly encountered. The capacity of the spillage system employed should then be selected for the maximum ambient temperature anticipated. These additional design considerations significantly influence inlet sizing and operation. For example, capture-area increases approaching 25 percent (fig. 7) and spillage capacity increases between 50 and 100 percent (fig. 8) are indicated.

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Figure 8 represents the total mass-flow spillage required, and includes any spillage ahead of the inlet lip behind either a normal shock or behind one or more oblique shocks. When designing for a constant ambient temperature only, it is possible that with certain inlet-engine combinations sufficient oblique-shock spillage may occur as the flight speed is varied to achieve essentially critical inlet operation continuously without the need of variable-geometry features. However, this inherent spillage from a fixed compression surface at below-design Mach numbers would not in itself be adequate when variations in ambient temperatures are considered. As can be seen in figure 8, up to 30 percent of the capture mass flow may be spilled at off-design ambient temperatures even at the design Mach number of 3.5.

Figure 9 demonstrates this same problem at design Mach numbers below 3.5. The curves represent on-design spillage of inlets sized for the cold-day condition and operated on both the NACA standard day and the Air Force hot day. It is apparent that considerable spillage is required at design Mach numbers as low as even 1.5. Clearly, variable geometry to accommodate this spillage is required to obtain efficient operation at even the design free-stream Mach number. Without it, variation in the ambient temperature can drive the inlet into buzz.

SUMMARY OF RESULTS

The following results were obtained from an analysis of the effect of ambient-temperature changes on turbojet-engine - supersonic-inlet matching requirements.

1. With engines designed for constant mechanical speed operation, changes in ambient temperature ordinarily encountered in flight can markedly influence the performance of the matched inlet-engine combination.

At the design free-stream Mach number, ambient temperatures below the design value force a fixed inlet to operate supercritically, whereas temperatures above design would cause subcritical operation. Changes of as much as 20 to 30 percent in either pressure recovery or mass flow can result.

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2. In order to make use of translating spikes or bypass systems installed for off-design free-stream Mach number operation the inlet should be sized for the lowest ambient temperature to be encountered at the design free-stream Mach number. The capacity of such spillage systems will probably be considerably larger than that required for only standard-day operation.

3. Those fixed-geometry inlet systems which rely on oblique-shock spillage for efficient inlet-engine airflow matching at below-design free-stream Mach number are heavily penalized when ambient-air temperature variations are considered.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 30, 1956

REFERENCES

1. Ratner, Benjamin: Temperature Frequencies in the Upper Air. Weather Bur., U.S. Dept. Commerce, Jan. 1946.

2. Wyatt, DeMarquis D.: An Analysis of Turbojet-Engine-Inlet Matching. NACA TN 3012, 1953.

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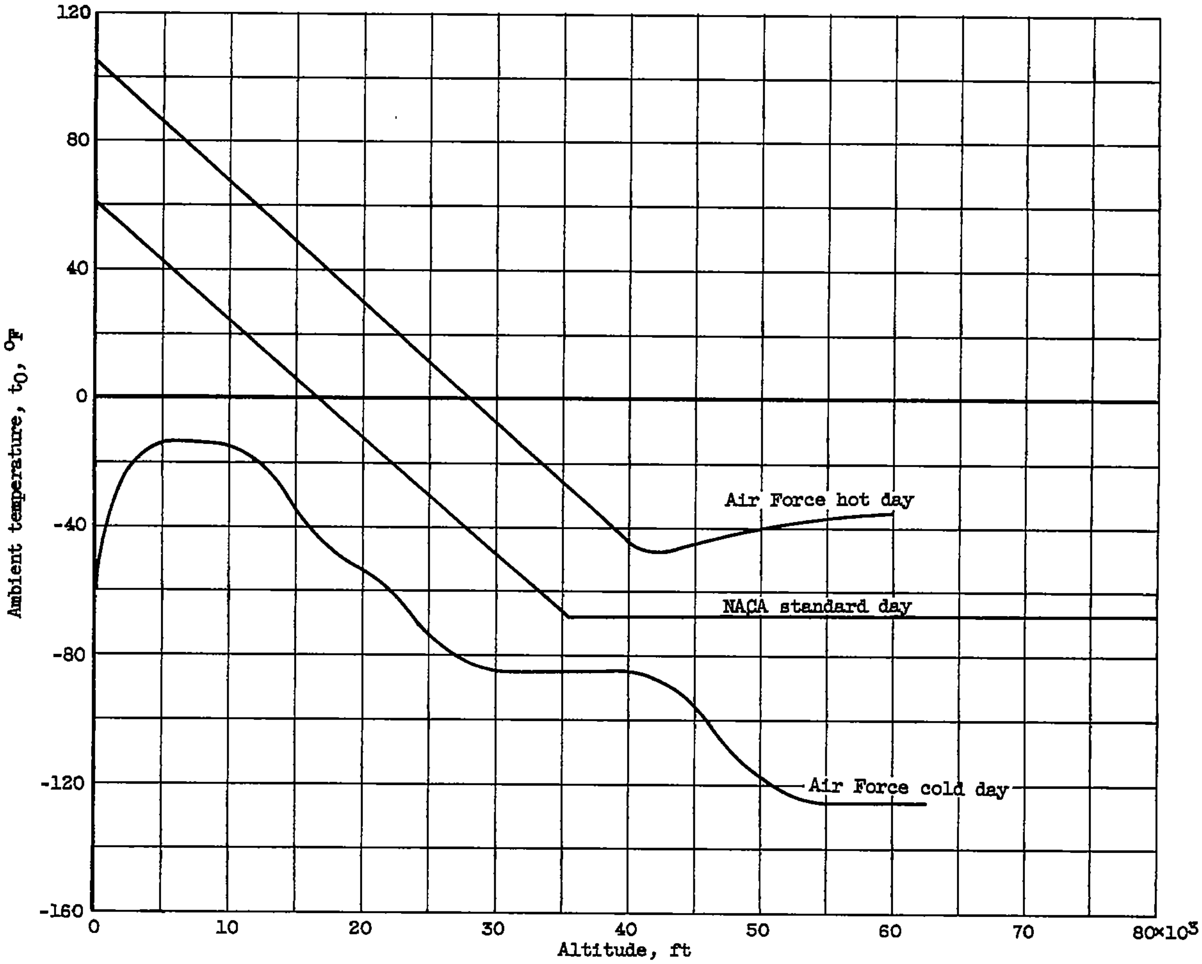

Figure 1. - Ambient-temperature variation for several standard days.

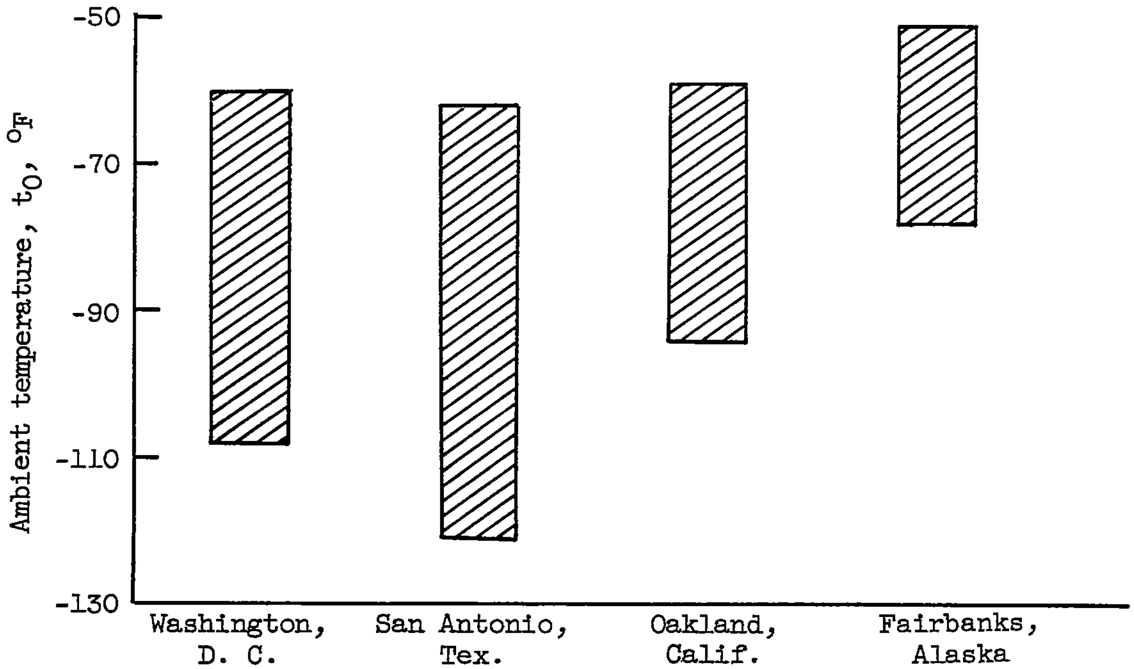

Figure 2. - Example of summer temperature variations at altitude of 52,600 feet. (Data from ref. 1.)

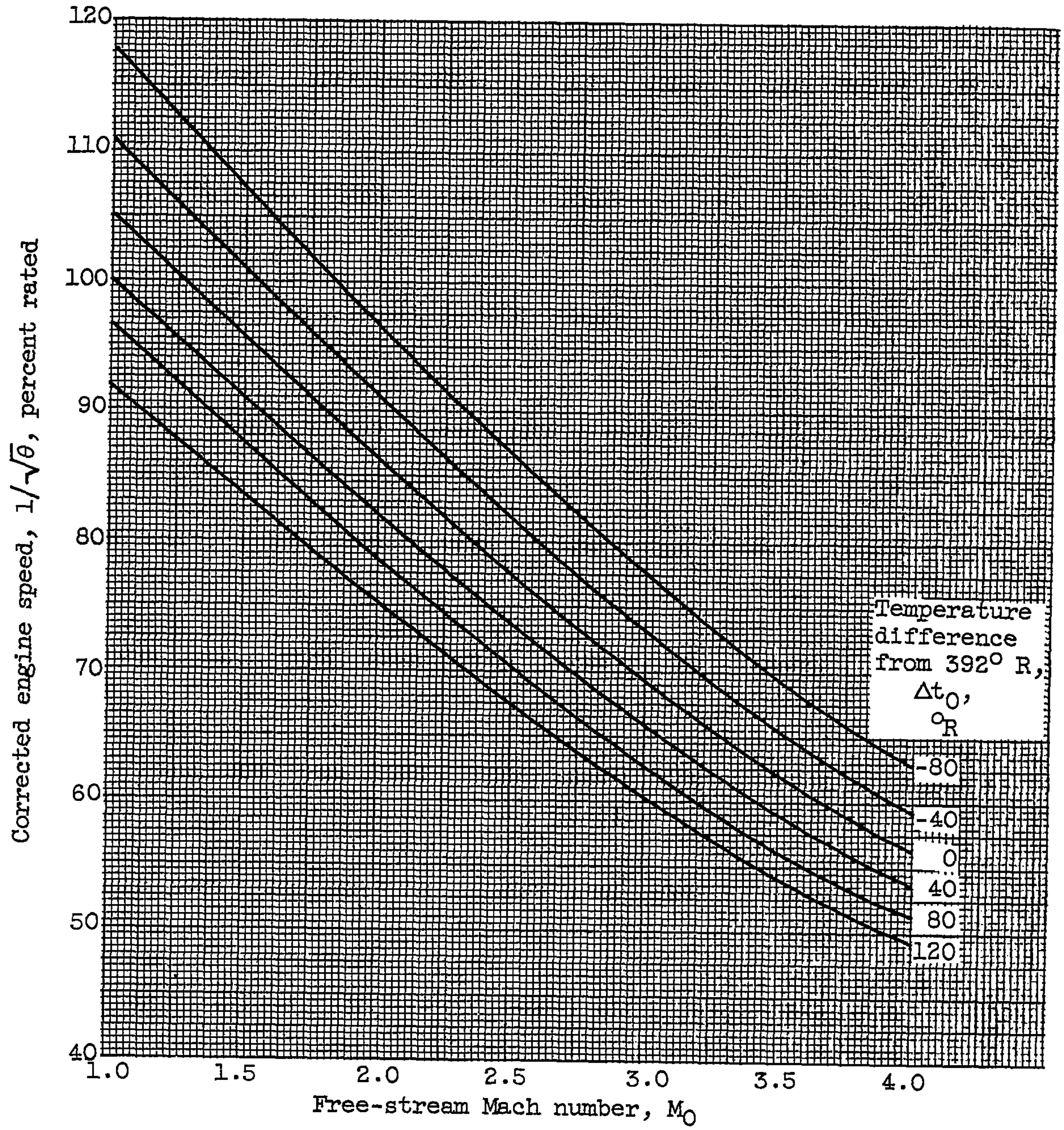

Figure 3. - Effect of ambient temperature on percent corrected engine speed at rated mechanical speed.

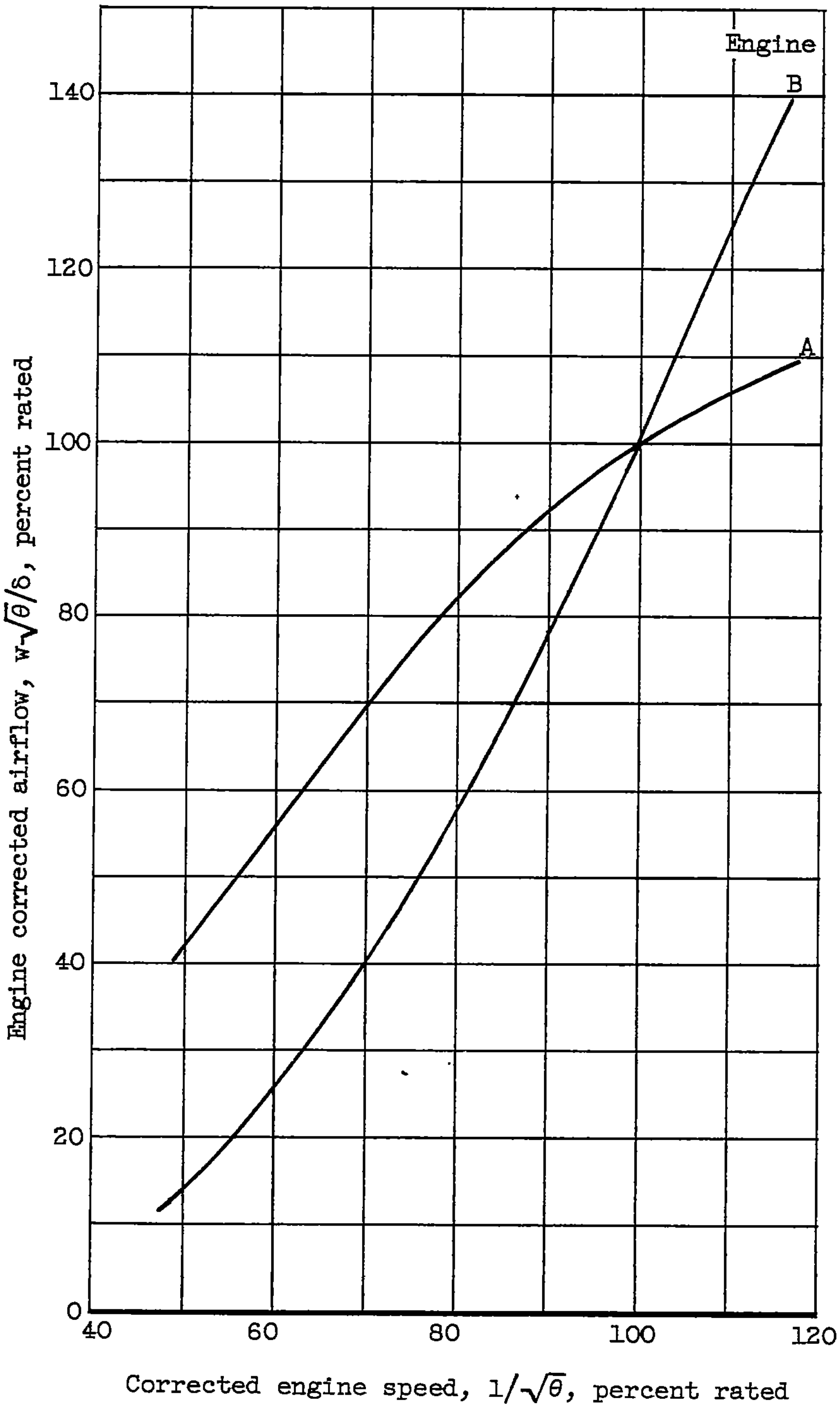

Figure 4. - Assumed engine airflow characteristics.

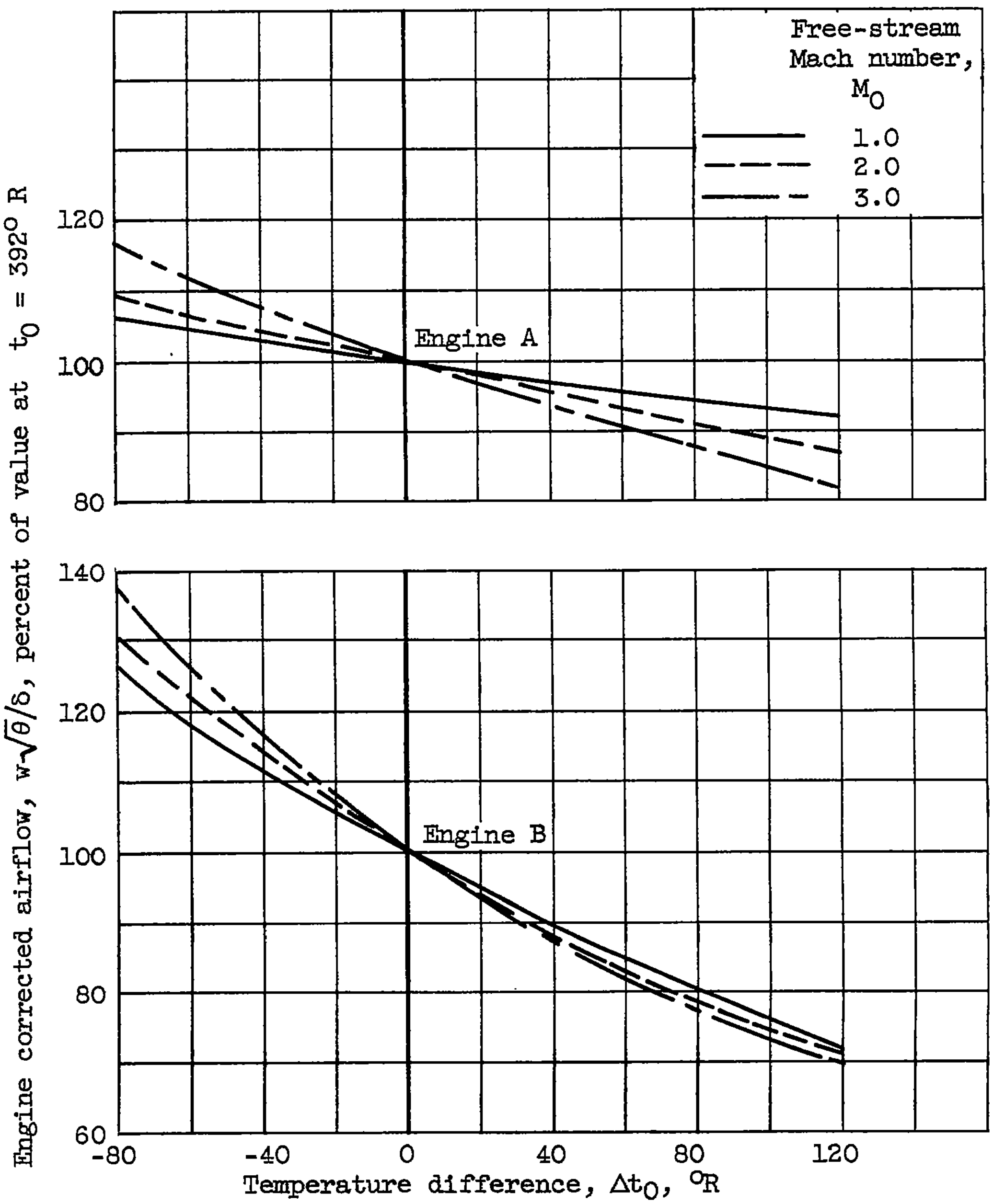

Figure 5. - Effect of ambient temperature on corrected engine airflow.

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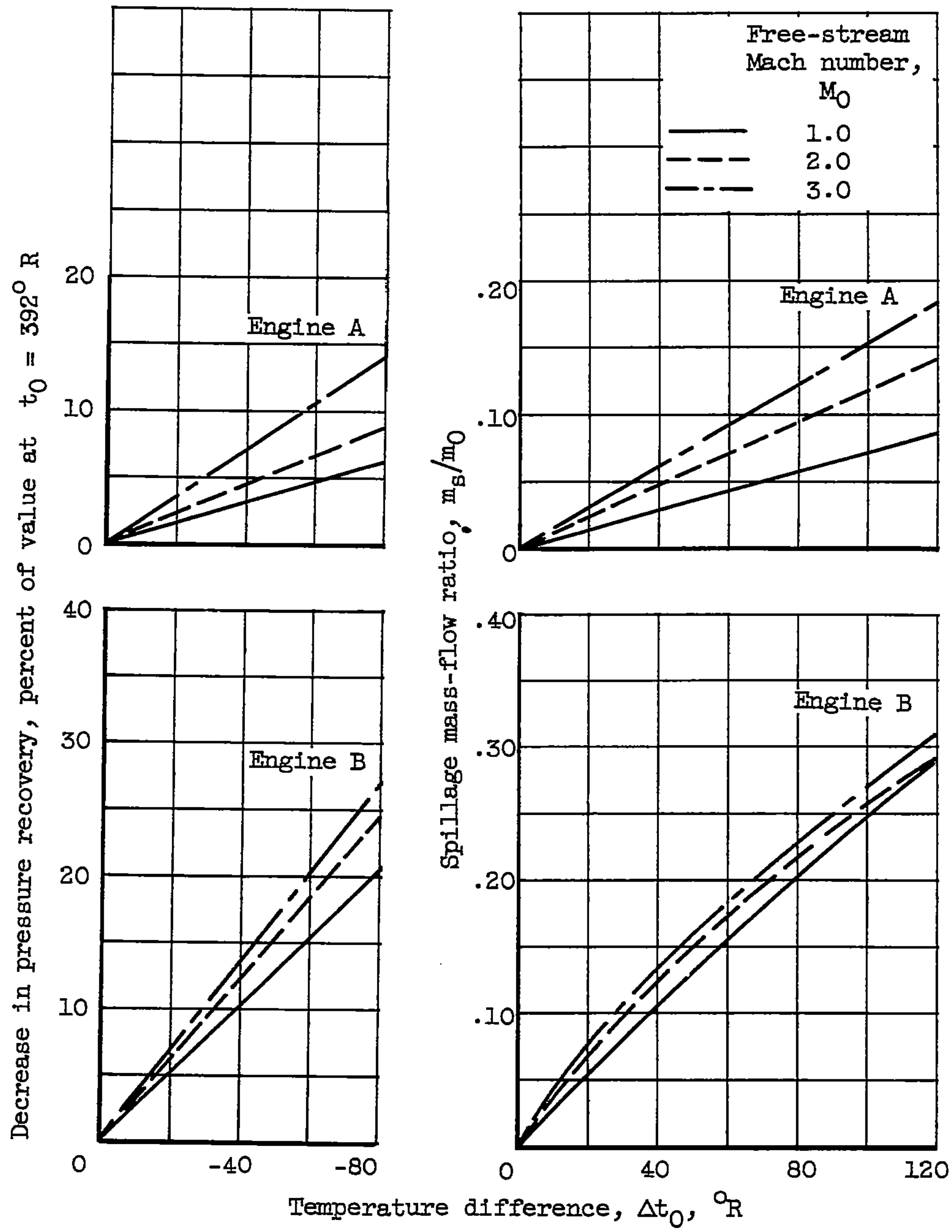
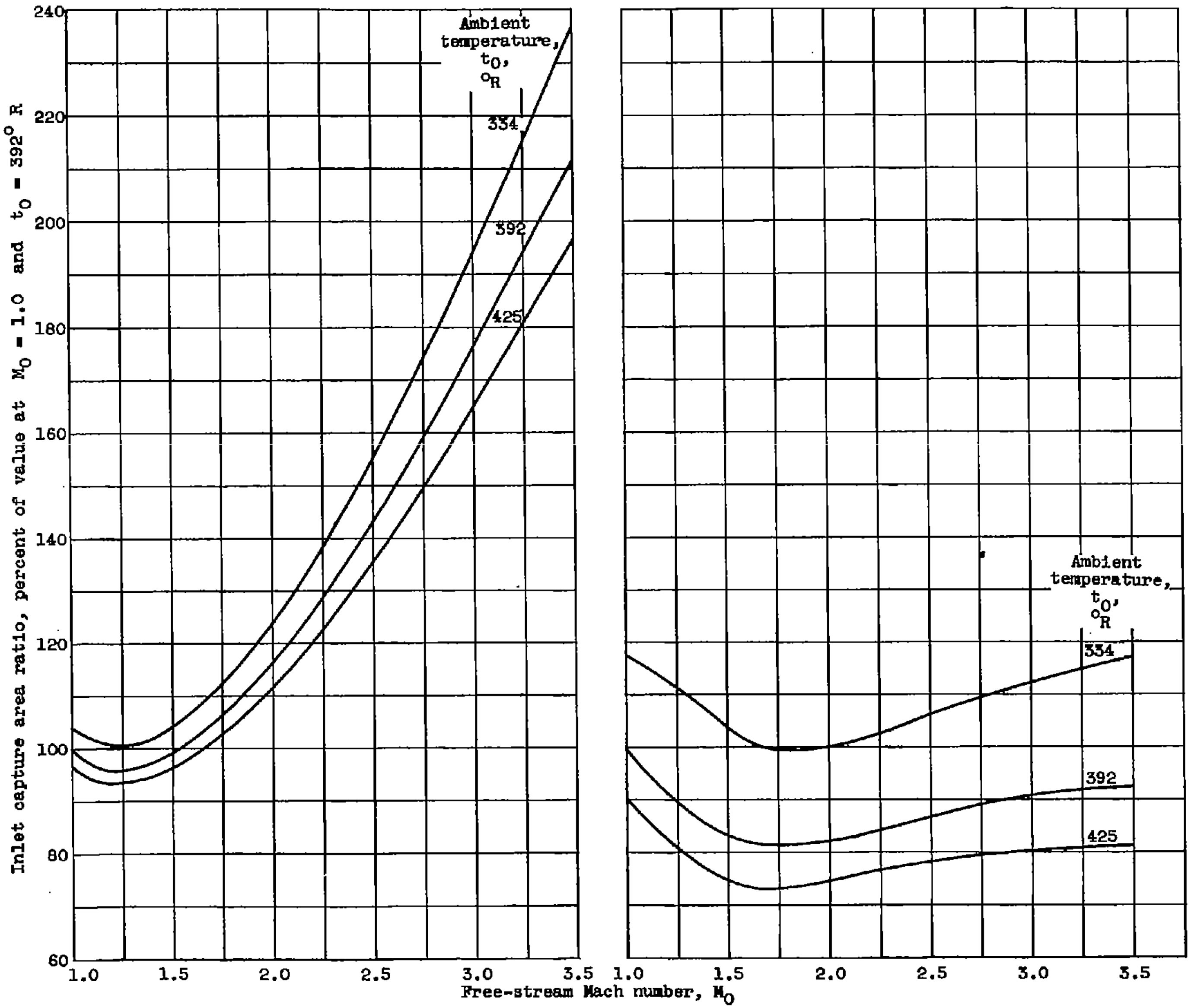


(a) Ambient temperature below design; inlet supercritical.

(b) Ambient temperature above design; inlet subcritical.

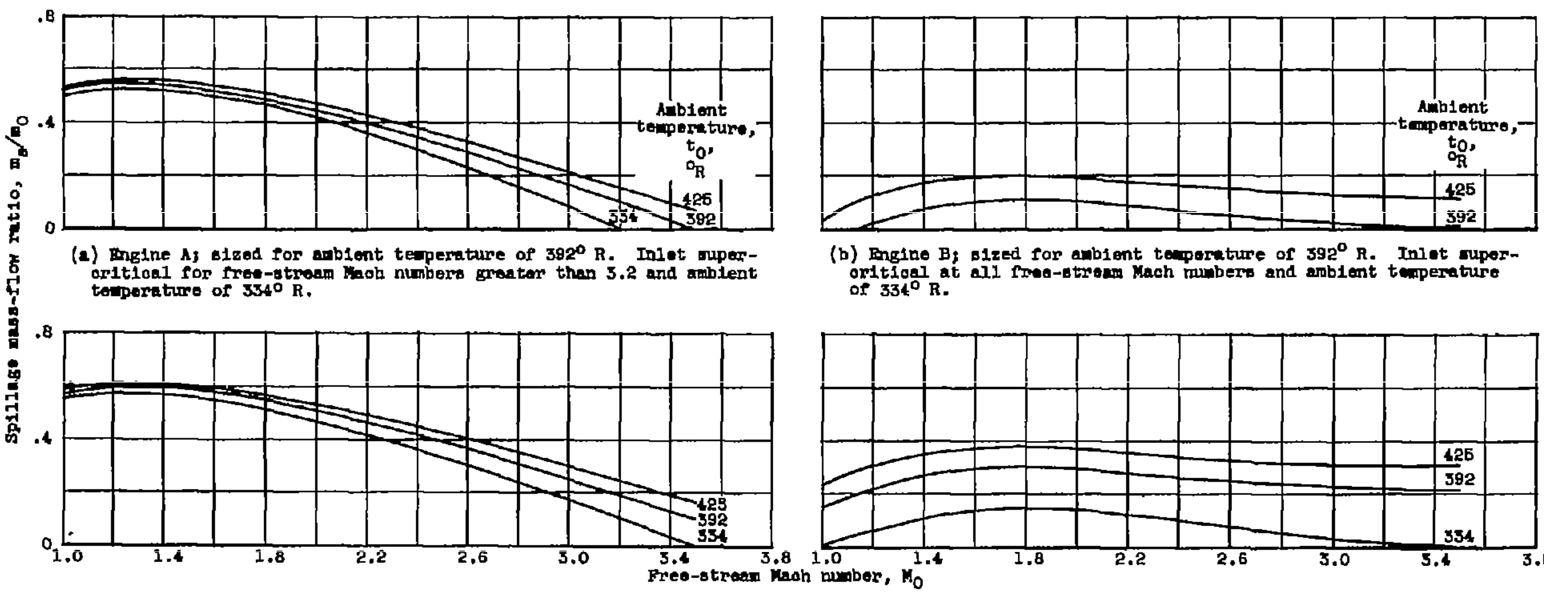
Figure 6. - Effect of ambient temperature on fixed inlet performance for inlet-engine combination critically matched at ambient temperature of 392° R.



(a) Engine A.

(b) Engine B.

Figure 7. - Effect of ambient temperature on required inlet capture area for critical inlet-engine matching.



(a) Engine A; sized for ambient temperature of 392° R. Inlet supercritical for free-stream Mach numbers greater than 3.2 and ambient temperature of 334° R.

(b) Engine B; sized for ambient temperature of 392° R. Inlet supercritical at all free-stream Mach numbers and ambient temperature of 334° R.

(c) Engine A; sized for ambient temperature of 334° R.

(d) Engine B; sized for ambient temperature of 334° R.

Figure 8. - Effect of ambient temperature on inlet spillage requirements. Inlet design for free-stream Mach number of 3.5.

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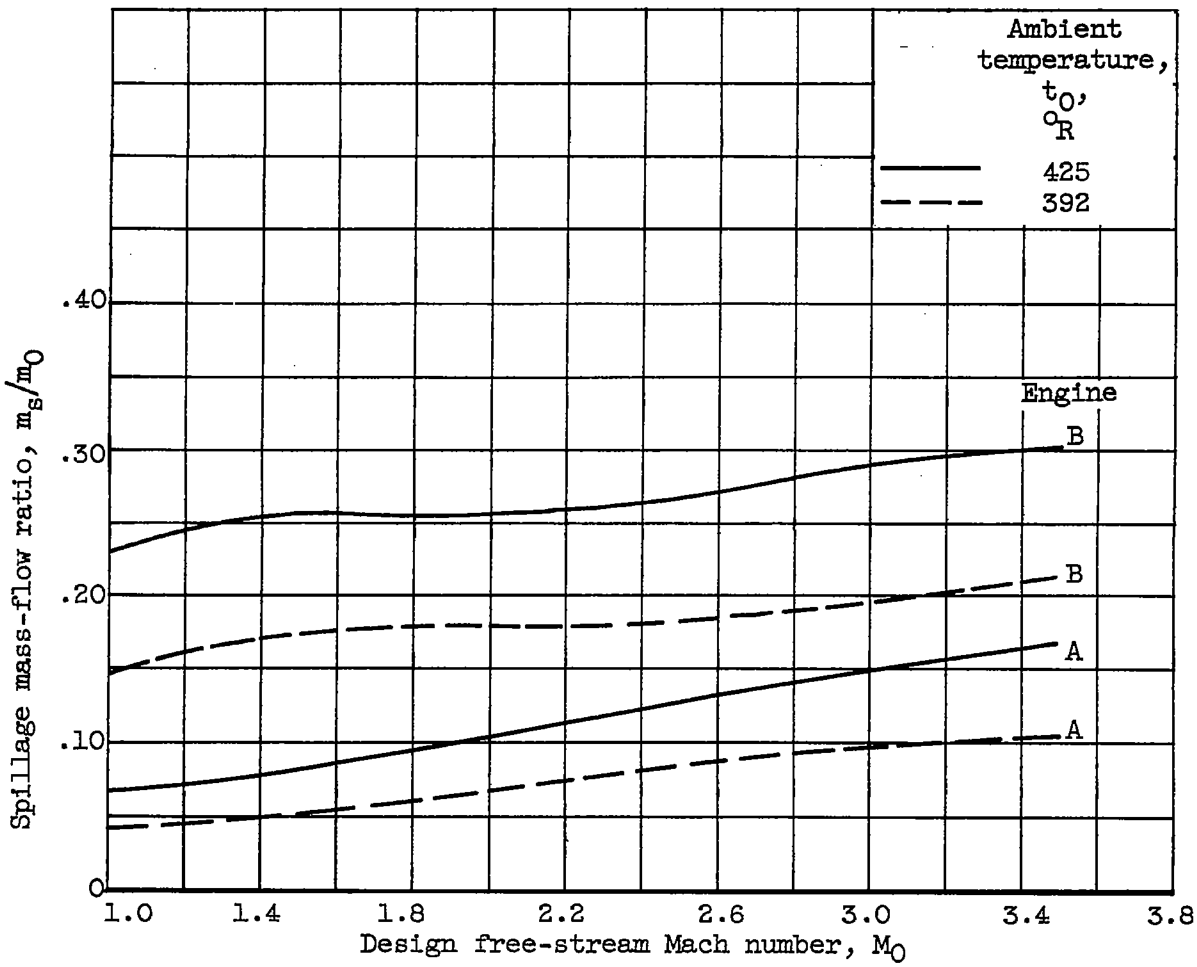

Figure 9. - Effect of design Mach number on ambient-temperature-induced spillage. Inlet sized for ambient temperature of 334° R.